SIMULATION ON THE EFFECT OF TEMPERATURE ON FORWARD OSMOSIS PROCESS ACROSS MEMBRANE

by

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Thesis submitted in fulfillment of the requirements for the degree of Bachelor of Chemical Engineering

January 2013
ABSTRACT

Forward Osmosis (FO) is one of the technologies that show a great performance in energy production and water supply. Forward osmosis is more preferred in both productions especially water supply because the purity of the water produce by forward osmosis technology is higher than other technology only by using low temperature, low pressure and low energy in the operation and also has low operating cost. The purposes of this research are to develop a process model program on forward osmosis process across the membrane and to use the develop model in order to investigate how the difference of temperature and concentration of draw solutions affects the forward osmosis process. The scopes of this research are more focus on the temperature where the range is from 20°C to 40°C, concentration of draw solution which is sodium chloride (NaCl) is from 1.0M to 2.5M and the type of membrane used is cellulose triacetate membrane (CTA). Besides, the simulation program is built based on the formulas adopted from a number of journals which are related to this research by using MATLAB software. By using the developed process model, the water purity produce was higher as the temperature and draw solution concentration increase. The results shown by the simulation are the same with the experiment result from other researcher. It shows both temperature and concentration has an important impact to water flux in forward osmosis process. Besides, this forward osmosis process model can be used as a foundation of the future research.
ABSTRAK

Forward Osmosis merupakan salah satu teknologi yang menunjukkan prestasi besar di dalam penghasilan tenaga dan bekalan air. Forward osmosis lebih banyak digunakan di dalam kedua industry terutama bekalan air kerana ketulenan air yang dihasilkan melalui proses forward osmosis adalah tinggi berbanding teknologi lain dengan hanya menggunakan suhu yang rendah, tekanan yang rendah, serta tenaga dan kos yang digunakan di dalam operasi ini juga sangat rendah. Tujuan penyelidikan ini dilakukan adalah untuk membina model simulasi terhadap process forward osmosis merentasi membran dan menggunakan model tersebut untuk mengkaji bagaimana perubahan suhu dan kepekatan cecair draw mempengaruhi proses forward osmosis. Penyelidikan ini lebih fokus kepada suhu di mana jurangnya adalah dari 20°C sehingga 40°C, kepekatan cecair draw iaitu natrium klorida (NaCl) adalah dari 1.0M sehingga 2.5M dan jenis membrane yang digunakan ialah membrane cellulose triacetate. Disamping itu, program simulasi ini dibina berdasarkan formula-formula yang diperolehi dari beberapa buah jurnal yang berkaitan dengan kajian ini dengan menggunakan perisian MATLAB. Dengan menggunakan model yang telah dibangunkan, ketulenan air yang dihasilkan akan meningkat seperlimana meningkatnya suhu dan kepekatan cecair draw. Hasil simulasi yang diperolehi adalah sama dengan hasil eksperiment yang diperolehi oleh penyelidik lain. Ini menunjukan bahawa kedua-dua suhu dan kepekatan memberi kesan penting di dalam proses forward osmosis. Selain itu, model proses forward osmosis in boleh digunakan sebagai asas kepada kajian akan datang.
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LIST OF EQUATIONS

General equation for water flux in the absence of polarization:

\[ J_w = A (\pi_{D,b} - \pi_{F,b}) \]  

(1)

Van’t Hoff Law:

\[ \pi_{F,m} = \beta_{F,s} C_{F,m} RT_{F,m} \]  

(2)

\[ \pi_{D,m} = \beta_{D,s} C_{D,m} RT_{D,m} \]  

(3)

\[ \pi_i = \beta_{F,s} C_i RT_i \]  

(4)

Modified water flux formula:

i) Active layer – Draw solution mode (AL-DS)

\[ J_w = A (\pi_{D,m} - \pi_i) = A \beta R \left( C_{D,m}T_{D,m} - C_iT_i \right) \]  

(5)

ii) Active Layer – Feed solution mode (AL-FS)

\[ J_w = A (\pi_i - \pi_{F,m}) = A \beta R \left( C_iT_i - C_{F,m}T_{F,m} \right) \]  

(6)

Concentration and dilution polarization:

\[ \frac{c_m}{c_b} = \exp \left( - \frac{J_w}{k} \right) \]  

(7)

i) Active layer – Draw solution mode (AL-DS)
\[
\frac{c_i}{c_{F,m}} = \exp (K_m J_w) \tag{8}
\]

ii) Active layer – Draw solution mode (AL-DS)

\[
\frac{c_i}{c_{D,b}} = \exp (-K_m J_w) \tag{9}
\]

Water permeability coefficient:

\[
A = \frac{D_{\text{eff}} C_w V_w}{\delta_m RT_i} \tag{10}
\]

\[
D_{\text{eff}} = D \left[ 1 - \frac{d_s}{d_p} \right]^4 \tag{11}
\]

\[
D = \frac{9.4 \times 10^{-15} \tau_i}{\mu_w M_w^{1/3}} \tag{12}
\]

\[
\mu_w = \rho_w \nu_w \tag{13}
\]

Mass transfer coefficient:

\[
k = \frac{Sh \ D_s}{d_h} \tag{14}
\]

Sherwood number:

1. Laminar flow : \( Sh = 1.85 \left( R_e Sc \frac{d_h}{L} \right)^{1/3} \) \( \tag{15} \)
2. Turbulent flow : \( Sh = 0.04 R_e^{3/4} Sc^{1/3} \) \( \tag{16} \)
Solute diffusivity:

\[ D_s = 8.931 \times 10^{-10} \left( \frac{n^+ + n^-}{n^+ n^-} \right) \left( y^+ y^- \right) T \]  

(17)

Reynolds number :

\[ R_e = \frac{ad}{v} \]  

(18)

Schmidt number :

\[ Sc = \frac{v}{D_s} \]  

(19)

Kinematic viscosity of NaCl solution:

\[ \frac{\nu}{\nu_w} = 1 + eC_s \exp \left( \frac{c_s f}{gT_R + 1} \right) \]  

(20)

\[ \nu_w = 9.607 \times 10^{-8} \exp \left[ \frac{2.9}{T_R^3} \right] \]  

(21)

\[ T_R = \frac{T}{273.15} \]  

(22)

Equivalent conductivity of the ions:

\[ \gamma^\pm = \gamma_{298.15}^\pm + \ell_1^\pm (T - 298.15) + \ell_2^\pm (T - 298.15)^2 + \ell_3^\pm (T - 298.15)^3 \]  

(23)

Solute resistivity :

\[ K_m = \frac{\tau \delta_m}{\varepsilon D_s} \]  

(24)
Heat flux:

\[
Q = h_{FS} (T_{F,b} - T_{F,m}) \\
= C_p \rho_w (T_{F,b} - T_{D,b}) - h_m (T_{D,m} - T_{F,m}) \\
= h_{DS} (T_{D,m} - T_{D,b})
\]  \(25\)

Temperature near membrane surface:

\[
T_{F,m} = \frac{h_m [T_{D,b} + \frac{h_{FS} T_{F,b}}{h_{DS}}] + h_{FS} T_{F,b} - C_p \rho_w (T_{F,b} - T_{D,b})}{h_m + h_{FS} \left[1 + \frac{h_m}{h_{DS}}\right]}
\]  \(26\)

\[
T_{D,m} = \frac{h_m [T_{F,b} + \frac{h_{DS} T_{D,b}}{h_{FS}}] + h_{DS} T_{D,b} + C_p \rho_w (T_{F,b} - T_{D,b})}{h_m + h_{DS} \left[1 + \frac{h_m}{h_{FS}}\right]}
\]  \(27\)

Temperature at interface at support and active layer:

\[
T_i = \frac{T_{F,m} + T_{D,m}}{2}
\]  \(28\)

Overall heat transfer coefficient of FO membrane:

\[
h_m = \frac{\varepsilon \lambda_w + (1 - \varepsilon) \lambda_m}{\delta_m}
\]  \(29\)

Modified solute diffusivity equation:

\[
D_s = 8.931 \times 10^{-10} \left[\frac{n^+ + n^-}{n^+ + n^-}ight] \left[\frac{\gamma^+ \gamma^-}{\gamma^+ + \gamma^-}\right] T
\]  \(30\)
**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Symbol</th>
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<tr>
<td>$A$</td>
<td>water permeability coefficient (m/sPa)</td>
</tr>
<tr>
<td>$C$</td>
<td>solute molar concentration (mol/L)</td>
</tr>
<tr>
<td>$C_i$</td>
<td>solute molar concentration at interface of SL and AL (mol/L)</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Specific heat (J/kgK)</td>
</tr>
<tr>
<td>$D_s$</td>
<td>diffusion coefficient (m$^2$/s)</td>
</tr>
<tr>
<td>$d_p$</td>
<td>diameter of membrane pore (m)</td>
</tr>
<tr>
<td>$d_h$</td>
<td>hydraulic diameter of the channel (m)</td>
</tr>
<tr>
<td>$h$</td>
<td>heat transfer coefficient (W/m$^2$K)</td>
</tr>
<tr>
<td>$J_w$</td>
<td>water flux (L/m$^2$h)</td>
</tr>
<tr>
<td>$k$</td>
<td>mass transfer coefficient (m/s)</td>
</tr>
<tr>
<td>$K_m$</td>
<td>solute resistivity (s/m)</td>
</tr>
<tr>
<td>$L$</td>
<td>characteristic length of the channel (m)</td>
</tr>
<tr>
<td>$M_w$</td>
<td>water molecular weight (g/mol)</td>
</tr>
<tr>
<td>$n^+$</td>
<td>valent of cations (dimensionless)</td>
</tr>
<tr>
<td>$n^-$</td>
<td>valent of anions (dimensionless)</td>
</tr>
<tr>
<td>$Q$</td>
<td>heat flux (W/m$^2$)</td>
</tr>
<tr>
<td>$R$</td>
<td>universal gas constant (J/molK)</td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynolds number (dimensionless)</td>
</tr>
<tr>
<td>$Sc$</td>
<td>Schmidt number (dimensionless)</td>
</tr>
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</table>
Sh  Sherwood number (dimensionless)

T  absolute temperature (K)

T_i  absolute temperature at interface SL and AL (K)

u  solution flow velocity (m/s)

V_w  water molar volume (m^3)

Greek letters

β  van’t Hoff coefficient (dimensionless)

γ^+  equivalent conductivity of cations (cm^2/Ω)

γ^-  equivalent conductivity of anions (cm^2/Ω)

δ_m  overall thickness of membrane (m)

ε  porosity of porous support layer (dimensionless)

μ  dynamic viscosity (kg/ms)

ν  kinematic viscosity (m^2/s)

π  osmotic pressure (Pa)

ρ  solution density (kg/m^3)

τ  tortuosity of porous support layer

Subscript

D, b  bulk draw solution

D, m  membrane surface draw solution

DS  draw solution

F, b  bulk feed solution
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tr>
<td>F, m</td>
<td>membrane surface feed solution</td>
</tr>
<tr>
<td>FS</td>
<td>feed solution</td>
</tr>
<tr>
<td>m</td>
<td>membrane</td>
</tr>
<tr>
<td>W</td>
<td>water</td>
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CHAPTER ONE

INTRODUCTION

1.1 Background of Proposed Study

Forward osmosis (FO) is an osmotic pressure which separates water from dissolved solutes from low to high osmotic pressure region through a semi-permeable membrane (Zhao & Zou, 2011). Forward osmosis is said to be an emerging technology that shows a great performance in water supply and energy
production and it is mostly preferred in desalination, wastewater treatment, food and pharmaceutical processing fields (Zhao et al., 2012). Unlike the former method, forward osmosis has potential in achieving high water flux besides it only use low energy which leads to low operating cost and also operates in low temperature and pressure (Cath et al., 2006; Zhao & Zou, 2011).

1.2 Problem Statement

Forward osmosis is a remarkable new technology that turns muddy, contaminated water or seawater into new clean water that can be drink. There are many factors that affecting the rate of forward osmosis in order to obtain a high water flux. Some of the factors are temperature and concentration of draw solution. As forward osmosis is a new technology, there is no simulation programme been developed (Choi et al., 2011) however, only a few modelling programme for forward osmosis process across the membrane had been developed. Thus, this study intends to know the effect of temperature and concentration of draw solution on forward osmosis process across the membrane through a simulation programme.
1.3 Research Objectives

This study is guided by the following research objectives:

1.3.1 To build a simulation programme of the forward osmosis process.

1.3.2 To investigate the effect of temperature on forward osmosis process across the membrane.

1.3.3 To investigate the effect of draw solution concentration on forward osmosis process across the membrane.

1.4 Scope of Study

This research is focus on the effect of temperature and concentration of draw solution on forward osmosis across the membrane by using MATLAB programme in order to develop the simulation process. Besides that, the type of membrane used in this forward osmosis process is cellulose triacetate (CTA) membrane.
1.5 Expected Outcomes

From this research, it is expected that the results from the simulation process model will be the same as the results obtained from experiments from other researchers. The purity of the water will be higher as temperature and draw solution concentration increase. This is due to several factors where the higher the temperature and concentration, it will cause the decreased of fluid viscosity and concentration polarization while at the same time the water permeability and mass transfer coefficient will increased. Thus, a higher water flux is obtained (Zhao & Zou, 2011). The model is essentially a set of different equations that describes the changes taking place across the cellulose triacetate (CTA) membrane.

1.6 Significance of Proposal Study

The developed simulation model can be used as foundation of the future research in forward osmosis since it will allow the user to study and understand the relationships between the elements of the system without having to manipulate the actual system. This will certainly give many advantages to the users to investigate the process or system rather than using the real process in term of money and time.
1.7 Conclusion

This report is divided into five chapters which are introduction, literature review, mathematical model of forward osmosis, results and discussion and conclusion and recommendation. Chapter one is divided into seven sub topics which are background of proposed study, problem statement, research objective, scope of proposed study, expected outcome, significance of proposed study and conclusion of the chapter. The second chapter consists of introduction of the chapter, the synthesis of all related articles and summary of the chapter. In chapter three, it includes the chapter introduction, the research methodology and summary. Chapter four consists of introduction, the result obtained from the research and the discussion made on the result. For chapter five, it will consist of conclusion and recommendation.
CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

The review of literature of this research study consists of six sections. Section 2.1 is the review on forward osmosis background and section 2.2 is the parameters of the forward osmosis. Review on the forward osmosis application and membrane will
be on section 2.3 and 2.4. The forward osmosis previous study is review in section 2.5 and 2.6 will be the conclusion.

2.2 Forward Osmosis Background

Forward osmosis is one of the new technologies used in the water treatment especially seawater and brackish water desalination and for the purification of the contaminated water sources (McGinnis, 2005). Generally, this technologies is highly used in industrial field because of its capability to remove difficult solutes in a waste streams. Forward osmosis is referred as a process that involves osmotic membrane where it diffuses polluted water spontaneously through a semi-permeable membrane from a low osmotic region (feed solution) to high osmotic region (draw solution) in order to produce hygienic water which can be drink safely (Cath et al., 2006; Gruber et al., 2011; Jung et al., 2011; Liu et al., 2009; Xu et al., 2010; Zhao & Zou, 2011).

Figure 2.1 show the process of forward osmosis. In forward osmosis, the membrane is located in between of feed solution and draw solution (permeate). During the process, the contaminated water will directly separate from the feed solution. The feed solution is used by the draw solution to force the water to pass through the semi-permeable membrane and as a result, the draw solution will be diluted while the feed solution will be more concentrated. Due to this reason, the initial concentrations of both feed and draw solution will not be equal. The semi-
permeable membrane will acts as an obstacle to block all the larger molecules from passing through the membrane and only allows the small molecules such as water to pass through it.

![Forward Osmosis Process](image)

**Figure 2.1** Forward Osmosis Process (*Source: HTI Water Technology*)

Forward osmosis is said as an emerging technology due to its potential to reduce the shortage of water and energy (Cath et al., 2006; Chung et al., 2012). Before forward osmosis, there are many other ways that have been used throughout the years to treat the water and one of the methods is by osmosis. Along with the technology development, the usage of the osmosis method is extended from water treatment to power generation. This is because water obtained from this method is more pure and the process is much easier. In past few years, the latest technology which is forward osmosis is introduced to the industries. Due to the potential shown by forward osmosis in water supply and power generation, forward osmosis is mostly preferred in wastewater treatment, desalination, power generation and food
processing fields (Zhao et al., 2012). Differ with reverse osmosis, forward osmosis is more preferred because it can be conducted in low hydraulic pressure, has low membrane fouling and requires less energy which leads to lower cost (Cath et al., 2006; Zhao et al., 2012). Besides the water treatment and power generation, forward osmosis also have been used for others applications.

### 2.3 Applications of Forward Osmosis

Recently, this forward osmosis technology is applied to a range of industries. This technology is separated into three fields which are life science, water and energy (Zhao et al., 2012). In the life science fields, forward osmosis are extensively used in food and pharmaceutical processing (Cath et al., 2006; Zhao et al., 2012). In food processing, forward osmosis is usually used to concentrate beverages and liquid foods. Since the forward osmosis process can be operated at low temperature and pressure, it helps to maintain the food quality and nutritional value such as flavour, aroma, colour and vitamins (Cath et al., 2006). For pharmaceutical industry, forward osmosis helps in controlling the drugs release (Cath et al., 2006).

As for water and energy, it is applied in wastewater treatment (Cath et al., 2006; Qin et al., 2009), landfills leachate (Cath et al., 2006), seawater desalination (Kessler & Moody, 1976; McCutcheon et al., 2005; Zhao et al., 2012) and power generation (Yip et al., 2010). Landfill leachate contains many types of pollutants
such as organic and inorganic compounds, dissolved heavy metals and total dissolved solids (TDS). Normally, landfill leachate is treated by using the wastewater treatment facility. However, among all of the compounds contains in the landfill leachate, the TDS is not only untreated but on the other hand enlarged the concentration of the TDS (York et al., 1999). Thus, in order to treat the TDS, forward osmosis has been used and it is proved that forward osmosis is very efficient in treating landfill leachate (York et al., 1999). Before forward osmosis is introduced, desalination and water treatment was treated by using the former membrane technologies such as reverse osmosis. However, energy issue had been arise when the former technologies was used (Fane, 2011).

Forward osmosis also has been used for osmotic bioreactor membrane and direct fertigation which is for the fertilizers. For all of this applications, forward osmosis is preferred due to several benefits where it can operates in low hydraulic pressure (Cath et al., 2006; Gruber et al., 2011) and higher osmotic pressure (Zhao et al., 2011). Low hydraulic pressure leads to lower tendency of the membrane to foul (Gruber et al., 2011) where lower membrane fouling caused the water product to be increased and longer the membrane life (Zhao et al., 2012). Besides, forward osmosis only requires low energy consumption for water transport (Chung et al., 2012; Zhao et al., 2012). As a consequences from the lower energy needed, it can reduce the process costs and increase the water flux produce by forward osmosis (Zhao et al., 2012). In order to obtain pure water with a higher water flux in the water treatment, there are many parameters involved which can affect the rate of forward osmosis.